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# A Radio Device for Educational Purposes

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Helsinki Metropolia University of Applied Sciences

Bachelor of Engineering

Degree Programme in Electronics

Bachelor's Thesis

09 May 2016

Author(s) Title	Prabhat Khanal A Radio Device for Educational Purposes
Number of Pages Date	39 pages 09 May 2016
Degree	Bachelor's degree
Degree Programme	Electronics
Specialisation option	
Instructor(s)	Matti Fischer, Principal Lecturer
<p>The goal of this project was to study front end of a simple radio. In this project a basic transmitter-receiver system at 735 MHz was built. Then information signal of 50 MHz was sent through transmitter and received by receiver. Information signal was analysed and studied as it goes through various components of the radio.</p> <p>Before the start of this project, it was decided not to manufacture all the components which would be needed in this project by author himself because manufacturing all the components would take more time than the time allocated for final year project and need vast knowledge and research. Therefore Metropolia's inventory was searched for the components needed for this project, and depending on those components and their working frequency range, a transmitting frequency was selected. Components which were not found, like filters and antennas, were manufactured. After all components were available, they were tested. Their various performance parameters were studied and it was examined if these components would be suitable for this project or not. After studying all parameters, components were connected together and signal of 50 MHz was sent and received through 20 cm space wirelessly. The project have achieved its goal and was successful.</p> <p>If this project would be continued, bandpass filter designed in this project should be tuned more or a new bandpass filter with well-tuned frequency response should be designed. How well this transmitter-receiver system would work with real life information signals, instead of using information signal from signal generator as done in this project, should be studied.</p>	
Keywords	Radio, receiver, transmitter, antenna, filter, VCO, mixer

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## List of abbreviations

VCO:	Voltage controlled oscillator
VFO:	Voltage variable oscillator
RF:	Radio frequency
IF:	Intermediate frequency
LO:	Local oscillator
LNA:	Low noise amplifier
FM:	Frequency modulation
PM:	Phase modulation
SSB:	Single side band
USB:	Upper side band
LSB:	Lower side band
MWO:	Microwave office
EM:	Electromagnetic
TEM:	Transverse electric magnetic
CAD:	Computer aid design
AUX_OUT:	Auxiliary output
MAIN_OUT:	Main output

## 1 Introduction

The intention of this project was to build a radio device for educational purposes. The original idea was to make front end of a simple radio to learn and understand how a radio works.

In this project, only front end of a simple radio was studied. Thus in this paper various components like antenna, filters, mixers and voltage controlled oscillator were studied. Some of these components were ready made mini-circuits components where as some were fabricated during the project. The radio was used in air medium at 735 MHz frequency.

## 2 Basics of a Radio

### 2.1 Introduction to Radio

In simple terms, radio is transmission and reception of electromagnetic energy wirelessly through a space. This electromagnetic energy is also known as radio waves. The biggest use of radio waves is to carry information, such as sound, video or digital data by systematically changing (modulating) the property of the radiated waves, such as their amplitude, frequency, phase or pulse width. In normal practice, electromagnetic waves of frequencies ranging from 3 kHz to 300 GHz are called radio waves.

When sending information through a space, the information signal is converted into appropriate form or protocols of radio wave signal needed to transmit in the space. The device which transmits radio waves is called radio transmitter.

These radio waves consist of electrical waves and magnetic waves. Electrical and magnetic waves are orthogonal to each other and both waves are orthogonal to direction of propagation of the radio wave.

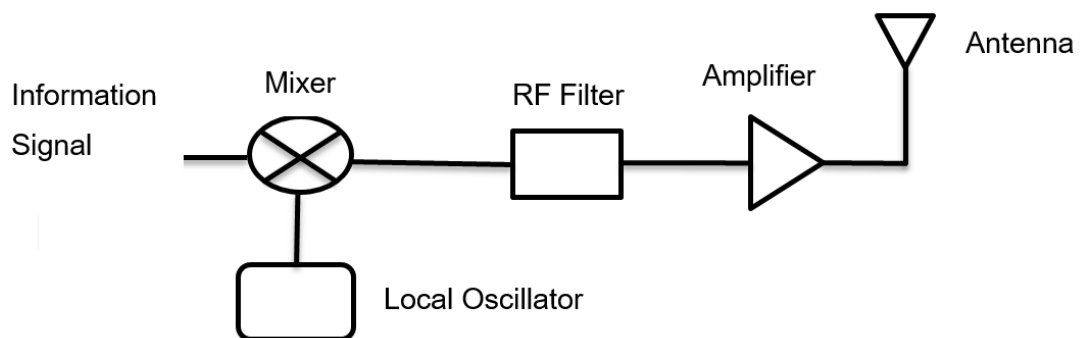
When radio waves strike a close loop electrical conductor, the magnetic wave of radio wave produces alternating current in the conductor. Whereas when radio waves strike an open loop electrical conductor, the electrical wave of radio wave produces alternat-

ing voltage across the conductor. The information is extracted from this alternating current or voltage using a device and transformed back into the original information signal. The device which receives the radio waves is called radio receiver.

## 2.2 Radio Transmitter

When sending (transmitting) the information wirelessly, in most cases the information signal is of low frequency signal. Mostly, a low frequency signal is not possible to be transmitted wirelessly due to size limitation of transmitting antenna, as well as signal attenuation in the space for various frequencies. For this purpose, first transmitting frequency is decided by considering the maximum size of transmitting antenna, as well as attenuation in the space for that frequency. Then a transmitter will convert information signal to the transmitting frequency and transmit the signal.

The basic building block of transmitter is as Figure 1:



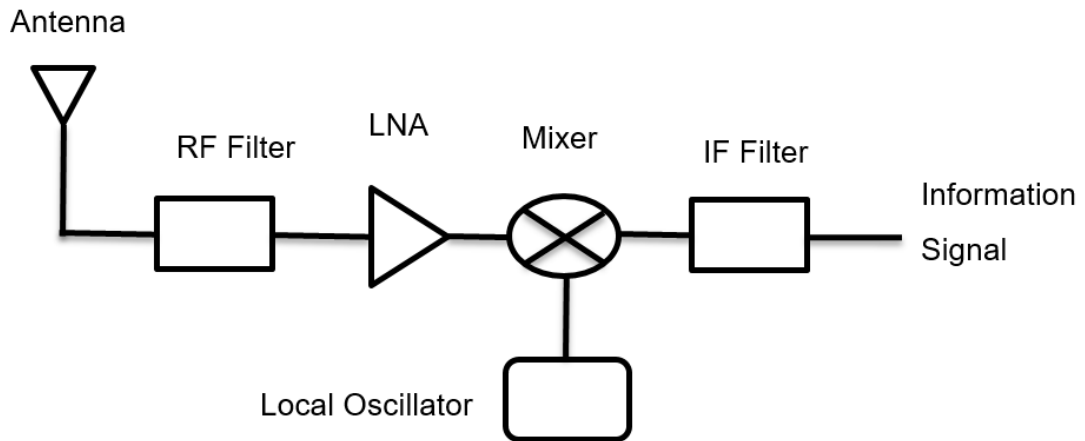
*Fig 1: Block diagram of radio transmitter*

In the transmitter chain, the information signal is mixed with local oscillator's output signal using a RF mixer. The RF mixer will produce sum and difference of frequencies of its input signals (i.e. information signal and local oscillator's output signal). The local oscillator output frequency is tuned so that the sum or difference of its output frequency and information signal frequency will be the transmitting frequency. Then the mixer's output goes through a RF filter. This filter is tuned so that it will only allow the transmitting frequency to pass through and block all others frequencies. This filtered signal is then amplified by an amplifier to the desired transmitting power level and then antenna is used to radiate the amplified signal into the space.

### 2.3 Radio Receiver

The receiving radio device should be tuned to the transmitting frequency to receive efficient radio wave.

The basic block diagram of receiver is as shown in figure 2:



*Fig 2: Block diagram of radio receiver*

In receiver chain, the radio signal is received by the antenna. Then this signal is filtered using a RF Filter. The RF filter is tuned so that it will only allow the signal whose frequency is the frequency in which the transmitter is transmitting the radio waves and block all others. LNA is low noise amplifier. It will amplify the filtered signal to desired power level. Then a RF mixer will produce sum and difference in frequencies of the amplified signal and local oscillator's output signal. The local oscillator is tuned so that the difference in frequencies of local oscillator's output signal and LNA's output signal will be original information signal's frequency. Then the mixer's output goes through an IF filter which will block all the unwanted frequency components of its input signal other than frequency component of original information. Hence information signal is received and recovered back.

## 2.4 Components Used in Radio

### 2.4.1 Local Oscillator

Local oscillator (LO) is a signal generator component which outputs signal with very constant frequency component. A local oscillator is an electronic oscillator used with a mixer to change the frequency of an input signal. This frequency conversion process, also called heterodyning, which produces the sum and difference in frequencies of LO's and input signal's frequency. This is very common in radios because processing a signal at a fixed frequency gives improved performance in the radio receiver.

Performance of the signal processing depends on the characteristics of the local oscillator. The local oscillator must produce a stable frequency with low harmonics. Stability must take into account of temperature, voltage, and mechanical drift as factors. The oscillator must produce enough output power to effectively drive subsequent stages of circuitry, such as mixers or frequency multipliers. It must have low phase noise where the timing of the signal is critical. In a channelized receiver system, the precision of tuning of the frequency synthesizer must be compatible with the channel spacing of the desired signals. [1] [2].

A crystal oscillator is one of the common type of local oscillator that provides good stability and performance at relatively low cost, but its frequency is fixed, so changing frequencies requires changing the crystal. VCOs (voltage controlled oscillators) can also be used as local oscillator. VCOs are variable frequency oscillators (VFOs). There are many types of VFOs but here we will focus only VCOs.

VCOs are VFOs whose oscillation frequency is controlled by input voltage. DC input voltage will give constant frequency signal whereas modulating voltage applied to input of a VCO may output frequency modulated (FM) or phase modulated (PM) signals [3]. Voltage controlled oscillators can be broadly classified into linear voltage controlled oscillators and relaxation type voltage controlled oscillators.

Linear voltage controlled oscillators are generally used to produce a sinuous wave. In such oscillators an LC tank circuit is used for producing oscillations. An active element like transistor is used for amplifying the output of the LC tank circuit to compensate the energy lost in the tank circuit and to establish the necessary feedback conditions. Here



a varicap (variable capacitance) diode is used in place of the capacitor in the tank circuit. Varicap diode is a type of semiconductor diode whose capacitance across the junction can be varied by varying the voltage across the junction. Thus by varying the voltage across the varicap diode in the LC tank circuit, the output frequency of the VCO can be varied [4].

Relaxation type voltage controlled oscillators are used to produce a sawtooth or triangular waveform. This is achieved by the gradual charging and sudden discharge of a capacitor connected appropriately to an active element (UJT, PUT etc.) or a monolithic IC (LM566 etc.). Nowadays relaxation type VCOs are generally realized using monolithic ICs. [3] [4]. They can provide a wide range of operational frequencies with a minimal number of external components. Relaxation oscillator VCOs can have three topologies: 1) grounded-capacitor VCOs, 2) emitter-coupled VCOs, and 3) delay-based ring VCOs. The first two of these types operate similarly. The time spent in each state depends on the rate of charge or discharge of a capacitor. The delay-based ring VCO operates somewhat differently however. For this type, the gain stages are connected in a ring. The output frequency is then a function of the delay in each stage.

Linear oscillator VCOs have following advantages over relaxation oscillators:

- Frequency stability with respect to temperature, noise and power supply is much better for harmonic oscillator VCOs.
- They have good accuracy for frequency control since the frequency is controlled by a crystal or tank circuit.

A disadvantage of harmonic oscillator VCOs is that they cannot be easily implemented in monolithic ICs. Relaxation oscillator VCOs are better suited for this technology. Relaxation VCOs are also tuneable over a wider range of frequencies.

Tuning range, tuning gain and phase noise are the important characteristics of a VCO. Generally low phase noise is preferred in the VCO. The noise present in the control signal and the tuning gain affect the phase noise; high noise or high tuning gain imply more phase noise. Other important elements that determine the phase noise are the transistor's flicker noise ( $1/f$  noise), the output power level, and the loaded Q of the resonator. (See equation 1). The low frequency flicker noise affects the phase noise because the flicker noise is heterodyned to the oscillator output frequency due to the active devices non-linear transfer function. The effect of flicker noise can be reduced

with negative feedback that linearizes the transfer function (for example, emitter degeneration). [3] [4].

Leeson's expression for single-sideband (SSB) phase noise in dBc/Hz (decibels relative to output level per Hertz) is as follow:

$$L(f_m) = 10 \log \left[ \frac{1}{2} \left( \left( \frac{f_0}{2Q_L f_m} \right)^2 + 1 \right) \left( \frac{f_c}{f_m} + 1 \right) \left( \frac{FkT}{P_s} \right) \right] \quad (1)$$

Where  $f_0$  is the output frequency,  $Q_L$  is the loaded Q,  $f_m$  is the offset from the output frequency (Hz),  $f_c$  is the  $1/f$  corner frequency,  $F$  is the noise factor of the amplifier,  $k$  is Boltzmann's constant,  $T$  is absolute temperature in Kelvins, and  $P_s$  is the oscillator output power [3].

Commonly used VCO circuits are the Clapp and Colpitts oscillators. The more widely used oscillator of the two is Colpitts and these oscillators are very similar in configuration. These are shown in figure 3.

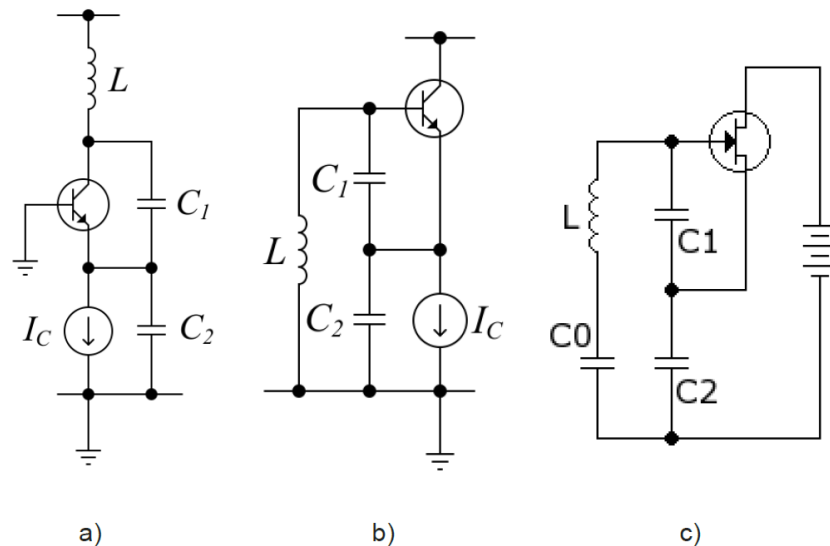


Fig 3: a) Common base Colpitts oscillator, b) Common collector Colpitts oscillator and c) Clap oscillator. [3].

In Colpitts oscillator frequency is defined as:

$$f_0 = \frac{1}{2\pi\sqrt{L\left(\frac{C_1C_2}{C_1+C_2}\right)}} \quad (2)$$

And in Clapp oscillator frequency is defined as:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{L}\left(\frac{1}{C_0} + \frac{1}{C_1} + \frac{1}{C_2}\right)} \quad (3)$$

VCOs generally have the lowest Q-factor of the used oscillators, and so they suffer more jitter than the other types. The jitter can be made low enough for many applications (such as driving an ASIC), in which case VCOs enjoy the advantages of having no off-chip components (expensive) or on-chip inductors (low yields on generic CMOS processes). These oscillators also have larger tuning ranges than the other kinds, which improves yield and is sometimes a feature of the end product (for instance, the dot clock on a graphics card which drives a wide range of monitors). [3].

#### 2.4.2 Mixer

RF mixing is one of the key processes within RF technology and RF design. RF mixing enables signals to be converted to different frequencies and thereby allows the signals to be processed more effectively.

##### 2.4.2.1 RF Mixing Basics

A mixer is a three-port device that uses a nonlinear or time-varying element to achieve frequency conversion. An ideal mixer produces an output consisting of the sum and difference frequencies of its two input signals. Operation of practical RF and microwave mixers is usually based on the nonlinearity provided by either a diode or a transistor. A nonlinear component can generate a wide variety of harmonics and other products of input frequencies, so filtering must be used to select the desired frequency components. Modern microwave systems typically use several mixers and filters to perform

the functions of frequency up-conversion and down-conversion between baseband signal frequencies and RF carrier frequencies.

When two signals enter an RF mixer and are mixed together, new signals are seen at frequencies that are the sum and difference of the two input signals, i.e. if the two input frequencies are  $f_1$  and  $f_2$ , then new signals are seen at frequencies of  $(f_1+f_2)$  and  $(f_1-f_2)$ . The mixing process is also shown in figure 4.

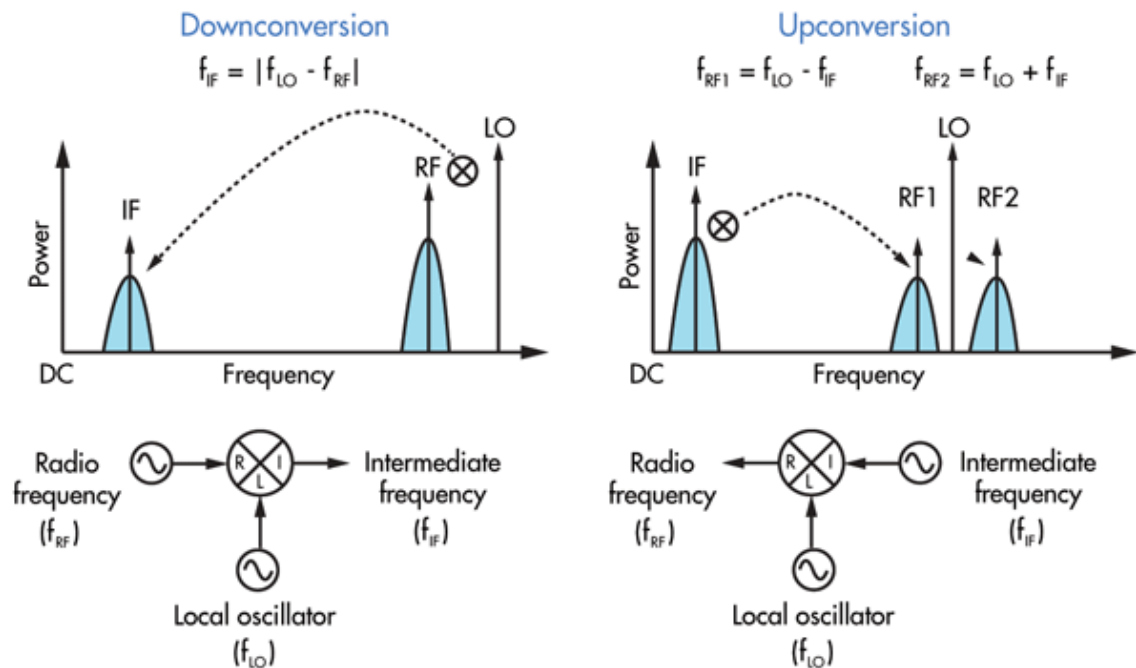


Fig 4: Mixing process.

The two input waveforms are represented by simple sine waves, and these are multiplied together. By expanding the resulting waveform using standard trigonometrical processes, it is possible to deduce what the output is.

If the input waveforms are taken as:

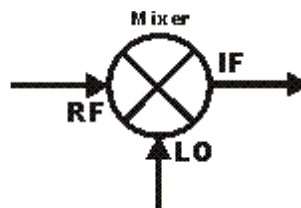
$$V_1 = A \sin(2\pi f_1 t) \text{ and } V_2 = B \sin(2\pi f_2 t) \quad (4)$$

Then in the RF mixer, the output is:

$$V_1 \times V_2 = \frac{1}{2} (A \times B) [\cos(2\pi(f_1 - f_2)t) - \cos(2\pi(f_1 + f_2)t)] \quad (5)$$

From this it can be seen that the two terms:  $(f_1 - f_2)$  and  $(f_1 + f_2)$  can be seen, and these represent the sum and difference frequencies that are seen on figure 4.

When specifying RF mixer, reference is often made to the three ports of the mixer as in figure 5. There are two input ports and one output port. These ports are all identified separately as each one have different characteristics. The signal input is often designated "RF" or "RF input". The other input is typically connected to the local oscillator and is normally termed "LO". The output is normally designated "IF" for intermediate frequency [8] [9].



*Fig 5: Circuit symbol for an RF mixer with different ports identified*

#### 2.4.2.2 Key RF Mixer Specifications

Although there are many elements responsible for the performance of an RF mixer, there are a number that are of key importance, and they are required for the basic specification of the mixer. [5] [6, 637-654].

##### RF Mixer Type

There is a wide variety of different RF design or circuit configurations for mixers. Typically the types that can be bought as circuit modules or items are of the double balanced diode ring variety. However it is also possible to design single diode mixers, balanced diode mixers, bipolar mixers, FET mixers, image rejection mixers etc.

##### Frequency Range

No single RF mixer will be able to operate at all frequencies. The circuit construction of components will determine the range over which the RF mixer can operate. Typically the double balanced mixers bought as circuit components contain transformers and these are the main frequency limiting elements. Despite these frequency limitations, RF

mixers are normally able to operate over considerable frequency ranges. However the frequency range must be considered when ordering an RF mixer.

### RF Mixer Impedance

The standard impedance for RF mixers is 50 ohms. It is important to ensure that the source impedance for the inputs and the load for the output are accurately matched to the required impedance. Often small attenuators may be added into the line to ensure that this is the case. If the ports are not accurately matched to the required impedance, mixer specifications such as the spurious signal and isolation will be impaired.

### Input Levels

It is important to ensure that the input levels for the RF mixer are met. The RF input will have a maximum input level it can tolerate. Beyond this the mixer may become overloaded and the levels of spurious signals will rise above their limits, along with the isolation falling outside its specification.

The LO input is designed to have a certain input level and this should be maintained reasonably accurate. If it raises too high then higher levels of LO signal will appear at the output. Additionally higher levels of spurious may be experienced. If the signal level is too low, then the conversion loss may increase. Typically a tolerance of  $\pm 3$  dB is normally acceptable.

There are a few standard LO input levels. 7 dBm is standard for many RF mixing applications, whereas higher LO levels may be required when higher levels of RF input level is needed.

### Mixer Conversion Loss

The conversion loss of an RF mixer is a measure of its efficiency. The RF mixer conversion loss is defined as the ratio of the level of one of the output sidebands to the level of the RF input. This ratio is expressed in dB.

As only half of the input power can ever exist in one of the sidebands, this means that the best conversion loss that can ever exist in a diode mixer is 3 dB. However, other losses are also present in the mixer. These occur as a result of diode insertion loss, spurious signal generation, transformer core loss, etc. As would be expected, the conversion loss of the RF mixer will deteriorate towards the edges of the specified frequency band, mainly as a result of increase in transformer losses.

The conversion loss is also found to be a function of the carrier drive level, increasing particularly if the LO drive level is not correct. However, it is also found that the conversion loss can be improved by providing short circuit impedance at the output port for the undesired sideband. It is also necessary to provide external decoupling for the IF and RF ports of a single balanced mixer in order to achieve the specified conversion loss.

### Isolation

The port to port isolation is one of the parameters of the RF mixer that is of particular importance in most RF mixer applications. RF mixer isolation is defined as the ratio of the signal power available into one port of the mixer to the measured power level of that signal at one of the other mixer ports in a 50 ohm system. This is measured in dB.

Most RF mixer designs aim for the maximum isolation from the LO to the RF ports as the LO signal is normally the highest level. The LO to RF isolation is generally slightly less at the higher frequencies, and this is often important to ensure that the LO signal does not enter the RF drive circuitry and cause problems such as intermodulation. RF port to IF port isolation is poorest.

In a diode balanced or double balanced RF mixer, the isolation is determined by the equality of the diode dynamic characteristics and the accuracy of the transformer's balance. It is also found that a high level of second harmonic in the LO signal will also degrade the isolation performance because isolation deteriorates at high frequencies as a result of parasitic capacitance.

### Noise Figure

The noise figure for an RF mixer is important in radio receiver front end circuits. Any noise introduced by the RF mixer at an early stage in the receiver such as the first mixer, it will degrade the performance of the whole receiver. Thus the noise figure for the RF mixer is important. Above very low frequencies (typically around 10 kHz) the Schottky Barrier diodes used in balanced and double balanced diode mixers contribute negligible levels of noise. This means that the noise figure for the RF mixer is essentially its conversion loss.

### Spurious Signals

The basic mathematics used to illustrate the way in which an RF mixer works assumes that it is a perfect multiplier. (See equation 4 and 5). Unfortunately, this is not the case and signals in addition to the sum and difference frequencies are generated. The transfer characteristics for the diodes mean that harmonics for the input signals are generated. If the RF mixer was perfectly balanced, then these components would be cancelled out, but again this is not the case, and as a result, the harmonics of the two input signals also mix together. The lower odd ordered mixer products will be the highest level at the IF port or output of the RF mixer.

Levels of the spurious signals are dependent upon a number of factors. These include the LO and RF input levels as well as parameters such as the load impedance, temperature, frequency, etc. Many of these unwanted products will fall outside the required passband of the mixer, but most manufactured RF mixers will have data for these unwanted products which can be obtained from the manufacturer.

RF mixers are an important element in most RF designs. Accordingly, it is necessary to understand their limitations and know how to specify them to obtain the required performance.

#### 2.4.3 Filter

A filter is a two-port network used to control the frequency response at a certain point in an RF system by providing transmission at frequencies within the passband of the filter and attenuation in the stopband of the filter. Typical frequency responses include low-



pass, high-pass, bandpass, and band-reject characteristics. Applications can be found in virtually any type of RF communication, radar, or test and measurement system.

A filter allows signals through in what is termed the pass band. This is the band of frequencies below the cut off frequency for the filter. The cut off frequency of the filter is defined as the point at which the output level from the filter falls to 50% (-3 dB) of the in band level, assuming a constant input level. The cut off frequency is sometimes referred to as the half power or -3 dB point frequency. The stop band of the filter is essentially the band of frequencies that is rejected by the filter. It is taken as starting at the point where the filter reaches its required level of rejection.

The subject of RF filters is quite extensive due to the importance of these components in practical systems and the wide variety of possible implementations. In this project, filters are designed by the insertion loss method.

Insertion loss method uses network synthesis techniques to design filters with a completely specified frequency response. The design is simplified by beginning with low-pass filter prototypes that are normalized in terms of impedance and frequency. Transformations are then applied to convert the prototype designs to the desired frequency range and impedance level. Insertion loss methods of filter design lead to circuits using lumped elements (capacitors and inductors). [6, 380-415].

A perfect filter would have zero insertion loss in the passband, infinite attenuation in the stopband, and a linear phase response (to avoid signal distortion) in the pass-band. Of course, such filters do not exist in practice, so compromises must be made; herein lies the art of filter design. The insertion loss method, however, allows a high degree of control over the passband and stopband amplitude and phase characteristics, with a systematic way to synthesize a desired response. If, for example, a minimum insertion loss is most important, a binomial response could be used; a Chebyshev response would satisfy a requirement for the sharpest cutoff. If it is possible to sacrifice the attenuation rate, a better phase response can be obtained by using a linear phase filter design. In addition, in all cases, the insertion loss method allows filter performance to be improved in a straightforward manner, at the expense of a higher order filter. For the filter prototypes to be discussed below, the order of the filter is equal to the number of reactive elements. [6, 380-415].

There are quite many low pass filter prototypes. In this project, maximally flat low pass prototype will be used.

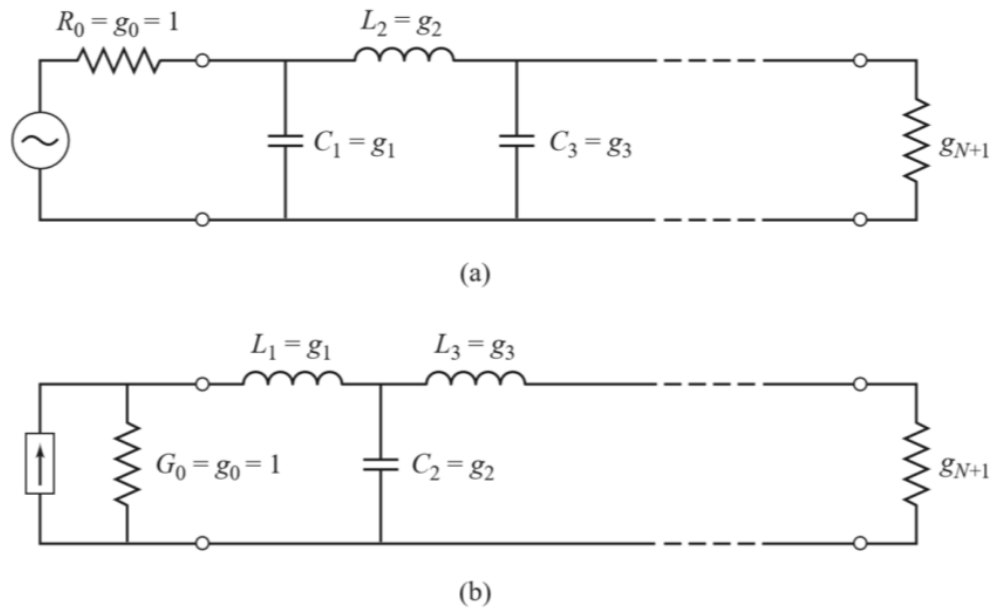


Fig 6: Ladder circuit for low-pass filter prototypes and their element definitions. (a) Prototype beginning with a shunt element. (b) Prototype beginning with a series element. [6, 403].

For a normalized low-pass design, where the source impedance is  $1\Omega$  and the cut-off frequency  $\omega_c = 1$  rad/sec, the element values for the ladder-type circuits of can be tabulated as shown in table 1. This table gives such element values for maximally flat low-pass filter prototypes for  $N = 1$  to 10. These data can be used with either of the ladder circuits of figure 6 in the following way.

The element values are numbered from  $g_0$  at the generator impedance to  $g_{N+1}$  at the load impedance for a filter having  $N$  reactive elements. The elements alternate between series and shunt connections, and  $g_k$  has the following definition:  $g_0$  = generator resistance or generator conductance;  $g_k$  ( $k = 1$  to  $N$ ) = inductance for series inductors or capacitance for shunt capacitors;  $g_{N+1}$  = load resistance if  $g_N$  is a shunt capacitor or load conductance if  $g_N$  is a series inductor.

Table 1: Element Values for Maximally Flat Low-Pass Filter Prototypes ( $g_0 = 1$ ,  $\omega_c = 1$ ,  $N = 1$  to 10) [6, 404].

$N$	$g_1$	$g_2$	$g_3$	$g_4$	$g_5$	$g_6$	$g_7$	$g_8$	$g_9$	$g_{10}$	$g_{11}$
1	2.0000	1.0000									
2	1.4142	1.4142	1.0000								
3	1.0000	2.0000	1.0000	1.0000							
4	0.7654	1.8478	1.8478	0.7654	1.0000						
5	0.6180	1.6180	2.0000	1.6180	0.6180	1.0000					
6	0.5176	1.4142	1.9318	1.9318	1.4142	0.5176	1.0000				
7	0.4450	1.2470	1.8019	2.0000	1.8019	1.2470	0.4450	1.0000			
8	0.3902	1.1111	1.6629	1.9615	1.9615	1.6629	1.1111	0.3902	1.0000		
9	0.3473	1.0000	1.5321	1.8794	2.0000	1.8794	1.5321	1.0000	0.3473	1.0000	
10	0.3129	0.9080	1.4142	1.7820	1.9754	1.9754	1.7820	1.4142	0.9080	0.3129	1.0000

After finding low pass prototype, transformation of prototype filter design parameters are done. Figure 7 shows how Lowpass prototype filter is transformed to other types of filters. For example when transforming Lowpass prototype filter to bandpass filter inductor is replaced by parallel inductor and capacitor whereas capacitor is replaced by series inductor and capacitor.

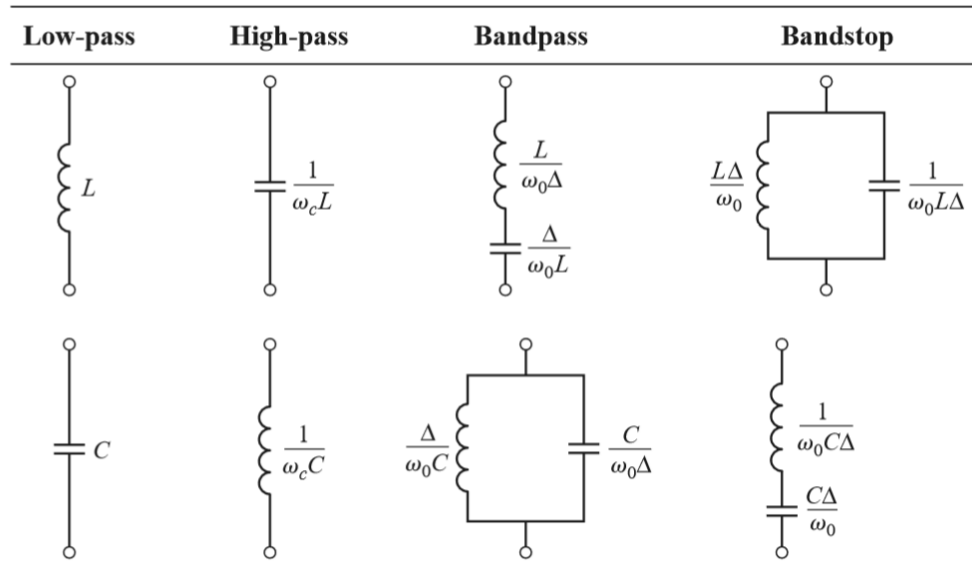


Fig 7: Prototype filter transformations ( $\Delta = \frac{\omega_2 - \omega_1}{\omega_0}$ ) [6, 414]

In this project 5<sup>th</sup> order band pass filter was designed. Values of lumped components were calculated as  $C1=0.92\text{pF}$ ,  $C2=51.5\text{pF}$ ,  $C3=0.28\text{pF}$ ,  $C4=51.50\text{pF}$ ,  $C5=0.92\text{pF}$ ,  $L1=49.18\text{nH}$ ,  $L2=0.88\text{nH}$ ,  $L3=0.16\text{nH}$ ,  $L4=0.88\text{nH}$ ,  $L5=49.18\text{nH}$ .

Capacitors and inductors with these values as chip components are very hard to find in market therefore these values were tuned to values which are available in market as standard chip packages using AWR microwave office CAD tool. Filter's circuit diagram was designed as figure 10, PCB layout was designed as figure 8 and simulation of S11 and S12 parameters was done as figure 9 in CAD tool.

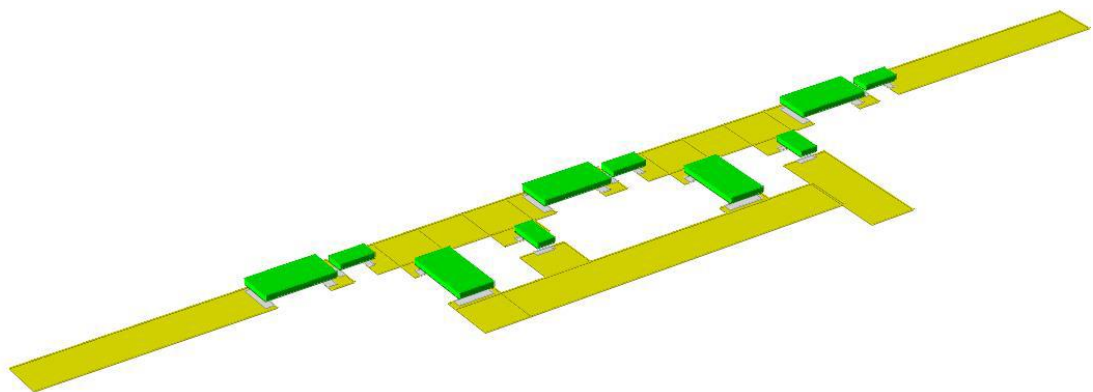


Fig 8: Filter PCB layout using Microwave office tool.

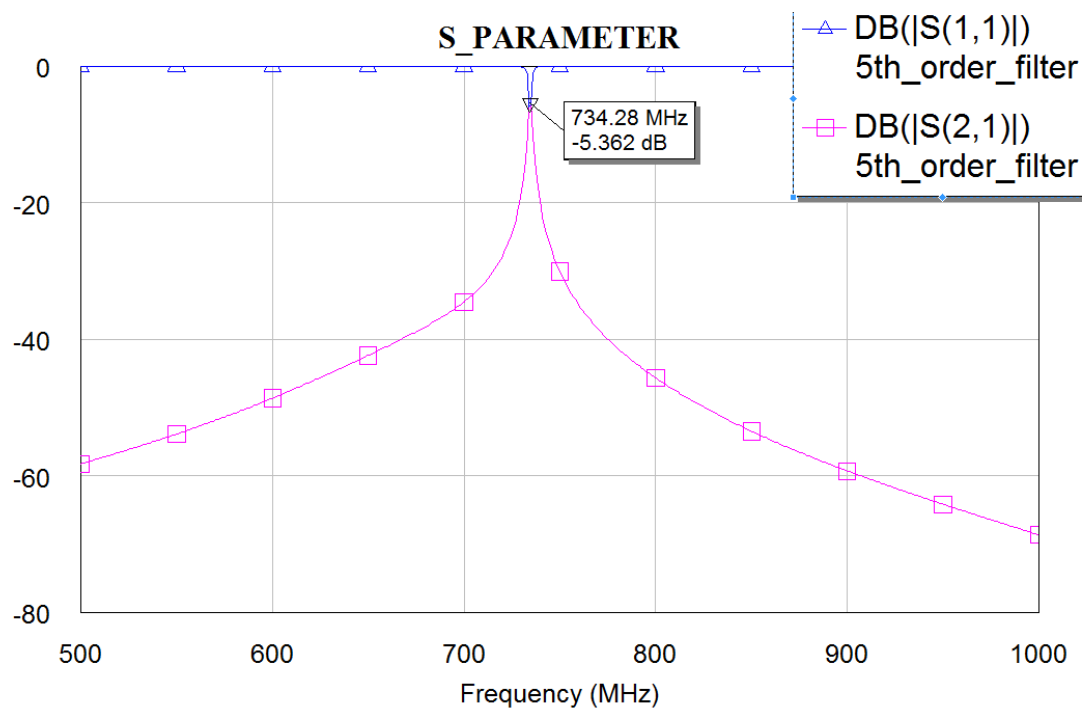


Fig 9: Frequency response of filter in Microwave office tool

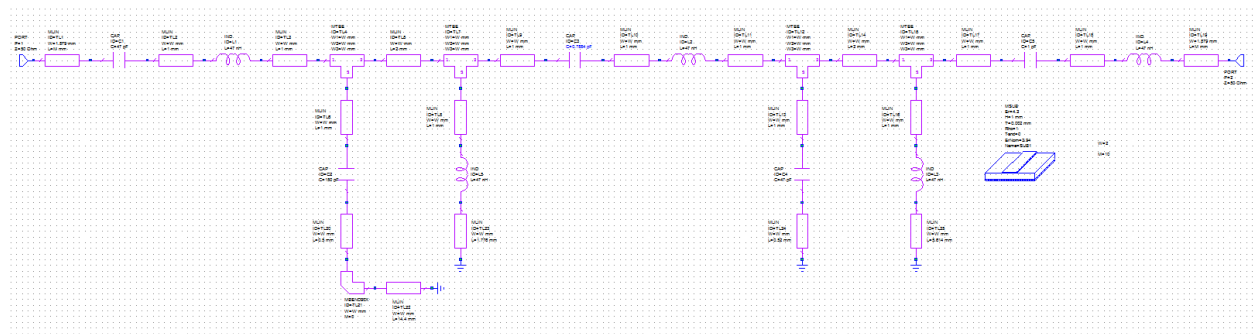


Fig 10: Circuit diagram using Microwave office tool

Then the filter was fabricated in FR4 board and lumped components were soldered and tested.

#### 2.4.4 Amplifier

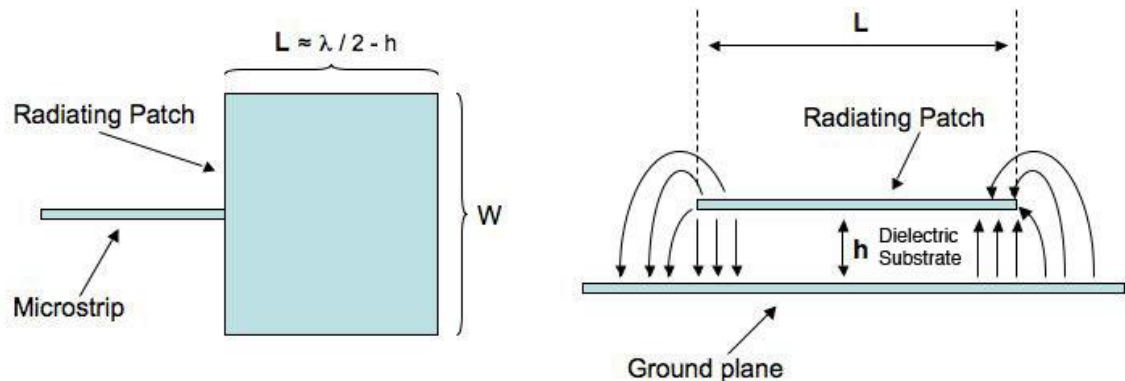
Amplifiers are used to increase the signal power level to desired level. In basic radio system amplifiers are one of key components. But for simplicity of this project amplifiers were not used here. Use of amplifier would have helped to increase the range of radio. Instead transmitting and receiving antenna were put close together so that sufficient level of power is received.

#### 2.4.5 Antenna

An antenna is mostly metallic device used to radiate or receive radio waves. An antenna can be any shape or size. A list of some common types of antennas is wire, aperture, microstrip, reflector, and arrays. Each antenna configuration has a radiation pattern and design parameters, in addition to their benefits and drawbacks [7, 1]. In this project, microstrip patch antenna was developed and used.

In its most basic form, a microstrip patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side as shown in

figure 11. The patch is generally made of conducting material such as copper or gold and can take any possible shape.



*Fig 11: Simple structure of patch antenna*

In order to simplify analysis and performance prediction, the patch is generally square, rectangular, circular, triangular and elliptical. For a rectangular patch, the length  $L$  of the patch is usually  $0.333 \lambda_0 < L < 0.5 \lambda_0$ , where  $\lambda_0$  is the free-space wavelength. The patch is selected to be very thin such that  $t \ll \lambda_0$  (where  $t$  is the patch thickness). The height  $h$  of the dielectric substrate is usually  $0.003 \lambda_0 \leq h \leq 0.05 \lambda_0$ . The dielectric constant of the substrate ( $\epsilon_r$ ) is typically in the range  $2.2 \leq \epsilon_r \leq 12$ . [7, 811-872] [8].

Microstrip patch antennas radiate primarily because of the fringing fields between the patch edge and the ground plane. For good antenna performance, a thick dielectric substrate having a low dielectric constant is desirable since this provides better efficiency, larger bandwidth and better radiation. However, such a configuration leads to a larger antenna size. In order to design a compact Microstrip patch antenna, higher dielectric constants must be used which are less efficient and result in narrower bandwidth. Hence, a compromise must be reached between antenna dimensions and antenna performance. [7, 811-872] [8].

Microstrip patch antennas are increasing in popularity for use in wireless applications due to their low-profile structure. Therefore they are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones.

The telemetry and communication antennas on missiles need to be thin and conformal and are often Microstrip patch antennas. Another area where they have been used

successfully is in Satellite communication. Some of their principal advantages are given below [8] [9]:

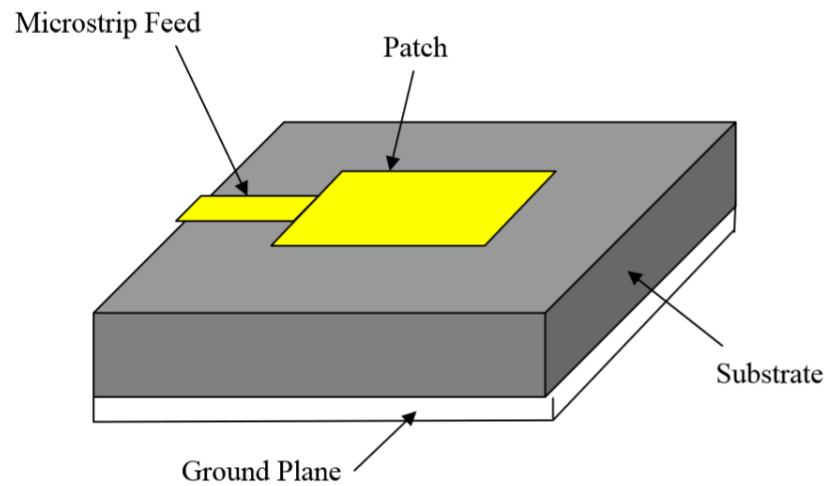
- Light weight and low volume.
- Low profile planar configuration which can be easily made conformal to host surface.
- Low fabrication cost, hence can be manufactured in large quantities.
- Supports both, linear as well as circular polarization.
- Can be easily integrated with microwave integrated circuits (MICs).
- Capable of dual and triple frequency operations.
- Mechanically robust when mounted on rigid surfaces.

Microstrip patch antennas suffer from a number of disadvantages as compared to conventional antennas. Some of their major disadvantages are given below [8] [9]:

- Narrow bandwidth
- Low efficiency
- Low Gain
- Extraneous radiation from feeds and junctions
- Poor end fire radiator except tapered slot antennas
- Low power handling capacity
- Surface wave excitation

Microstrip patch antennas have a very high antenna quality factor (Q). Q represents the losses associated with the antenna and a large Q leads to narrow bandwidth and low efficiency. Q can be reduced by increasing the thickness of the dielectric substrate. But as the thickness increases, an increasing fraction of the total power delivered by the source goes into a surface wave. This surface wave contribution can be counted as an unwanted power loss since it is ultimately scattered at the dielectric bends and causes degradation of the antenna characteristics. Other problems such as lower gain and lower power handling capacity can be overcome by using an array configuration for the elements [9].

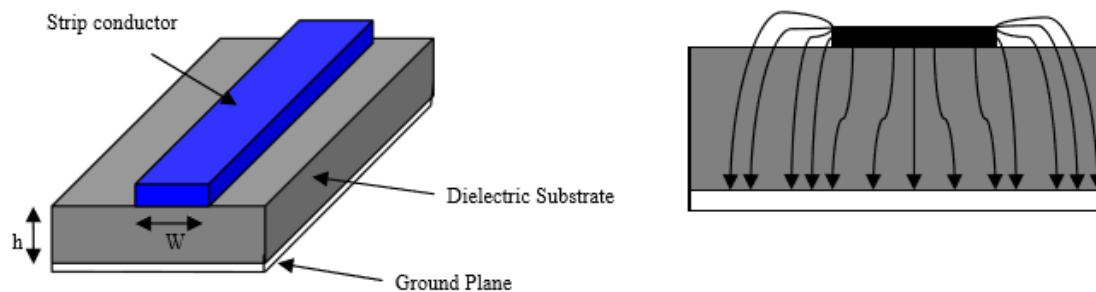
Microstrip patch antennas can be fed by many methods. One of the methods is Microstrip Line Feed method.



*Fig 12: Microstrip line feed method [8]*

In this type of feed technique, a conducting strip is connected directly to the edge of the microstrip patch as shown in Figure 12. The conducting strip is smaller in width as compared to the patch and this kind of feed arrangement has the advantage that the feed can be etched on the same substrate to provide a planar structure.

The purpose of the inset cut in the patch is to match the impedance of the feed line to the patch without the need for any additional matching element. This is achieved by properly controlling the inset position. Hence, this is an easy feeding scheme, since it provides ease of fabrication and simplicity in modelling as well as impedance matching. However, as the thickness of the dielectric substrate being used, increases, surface waves and spurious feed radiation also increases, which hampers the bandwidth of the antenna. The feed radiation also leads to undesired cross polarized radiation [7, 811-872] [8] [9].



*Fig 13: Microstrip line and electric field lines [8]*



The microstrip antenna is represented by two slots of width  $W$  and height  $h$ , separated by a transmission line of length  $L$  (See figure 11). The microstrip is essentially a non-homogeneous line of two dielectrics, typically the substrate and air.

Most of the electric field lines reside in the substrate and parts of some lines in air. As a result, this transmission line cannot support pure transverse electric-magnetic (TEM) mode of transmission, since the phase velocities would be different in the air and the substrate. Instead, the dominant mode of propagation would be the quasi-TEM mode. Hence, an effective dielectric constant ( $\epsilon_{\text{reff}}$ ) must be obtained in order to account for the fringing and the wave propagation in the line. The value of  $\epsilon_{\text{reff}}$  is slightly less than  $\epsilon_r$  because the fringing fields around the periphery of the patch are not confined in the dielectric substrate but are also spread in the air as shown in figure 11 and 13. [7, 811-872] [8]. The expression for  $\epsilon_{\text{reff}}$  is given as [7, 811-872] [8]:

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \quad (6)$$

Where  $\epsilon_{\text{reff}}$  = Effective dielectric constant

$\epsilon_r$  = Dielectric constant of substrate

$h$  = height of dielectric substrate

$W$  = Width of the patch

In order to operate in the fundamental  $10^{\text{th}}$  TM mode, the length of the patch must be slightly less than  $\lambda/2$  where  $\lambda$  is the wavelength in the dielectric medium and is equal to  $\frac{\lambda_0}{\sqrt{\epsilon_{\text{reff}}}}$  where  $\lambda_0$  is the free space wavelength. The  $10^{\text{th}}$  TM mode implies that the field varies one  $\lambda/2$  cycle along the length, and there is no variation along the width of the patch [7, 811-872] [8].

The fringing fields along the width can be modelled as radiating slots and electrically the patch of the microstrip antenna looks greater than its physical dimensions. The dimensions of the patch along its length have now been extended on each end by a distance  $\Delta L$ , which is given as [8]:

$$\Delta L = 0.412h \frac{(\epsilon_{\text{reff}} + 0.3) \left( \frac{W}{h} + 0.264 \right)}{(\epsilon_{\text{reff}} - 0.258) \left( \frac{W}{h} + 0.8 \right)} \quad (7)$$

The effective length of the patch  $L_{eff}$  now becomes:

$$L_{eff} = L + 2\Delta L \quad (8)$$

For a given resonance frequency  $f_0$ , the effective length is as:

$$L_{eff} = \frac{c}{2f_0 \sqrt{\epsilon_{reff}}} \quad (9)$$

For a rectangular Microstrip patch antenna, the resonance frequency for any  $mn$  TM mode is given as [8]:

$$f_o = \frac{c}{2\sqrt{\epsilon_{reff}}} \left[ \left( \frac{m}{L} \right)^2 + \left( \frac{n}{W} \right)^2 \right]^{\frac{1}{2}} \quad (10)$$

Where  $m$  and  $n$  are modes along  $L$  and  $W$  respectively. For efficient radiation, the width  $W$  is given as [8]:

$$W = \frac{c}{2f_o \sqrt{\frac{(\epsilon_r + 1)}{2}}} \quad (11)$$

After all calculations it was found that  $L_{eff} = 153.3$  millimetres and  $W = 112.6$  millimetres for the FR4 board available to us to design patch antenna at 735 MHz.

Then antenna was designed using AWR microwave office (MWO) CAD programme. Values calculated were tuned by MWO and fabricated in FR4 board and tested. The layout and circuit of antenna are seen in figure 14 and figure 16 and simulation of S11 parameter was looked as in figure 15.

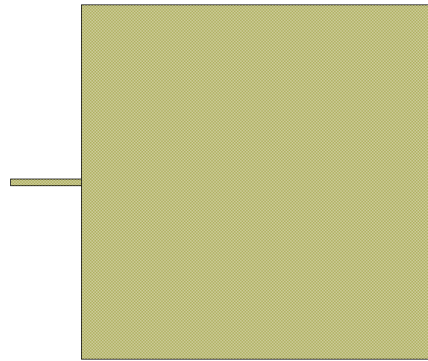


Fig 14: Antenna design in Microwave office.

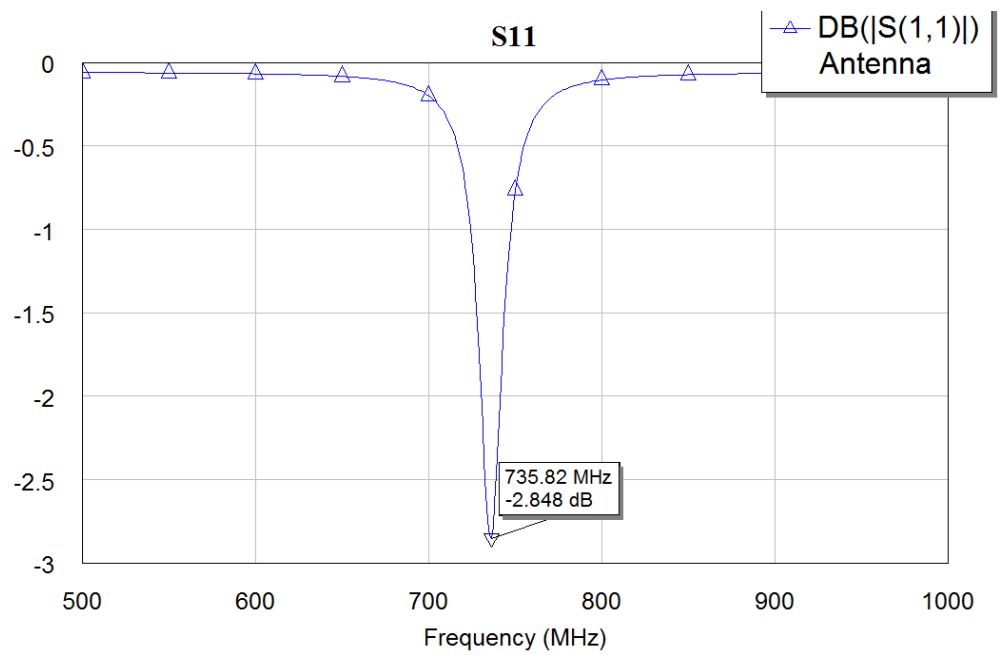


Fig 15: Frequency response in Microwave office tool

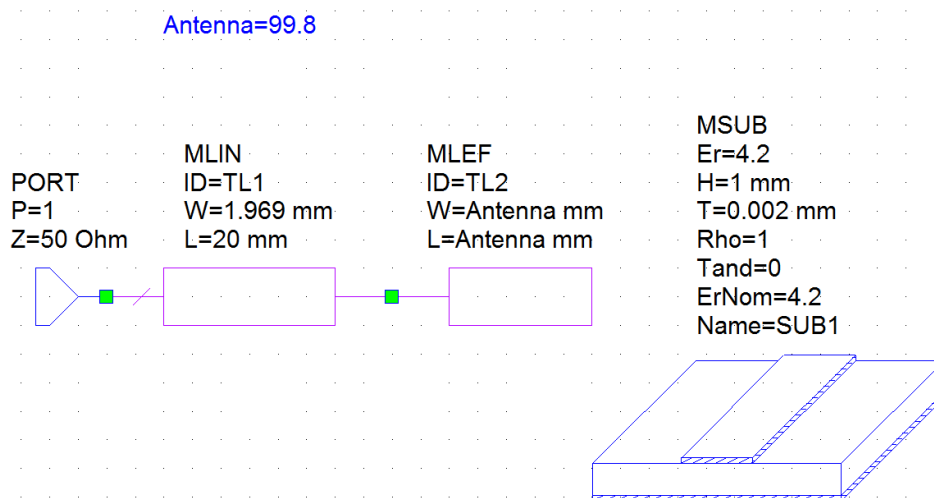


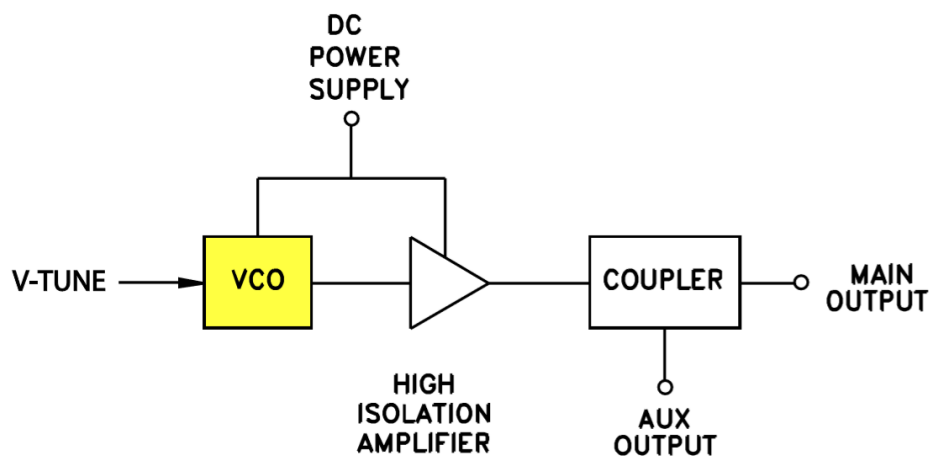
Fig 16: Circuit designed in Microwave office tool

### 3 Measurements

All of the measurements which were done by spectrum analyser had an attenuation of 10 dBm in the input port of spectrum analyser. Therefore in this report all power levels which were measured by spectrum analyser are 10 dBm less than the real power that should be seen in spectrum analyser.

#### 3.1 VCO Testing

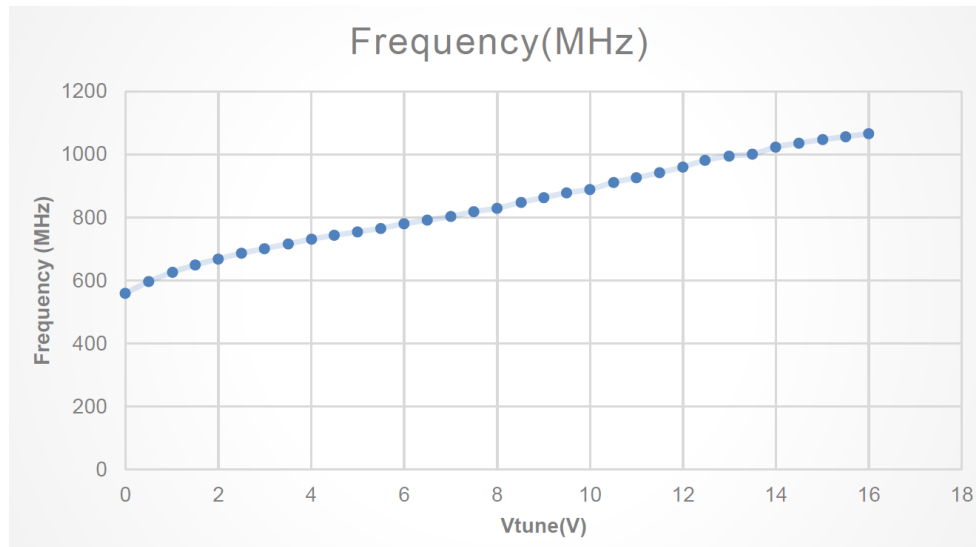
Voltage controlled oscillator used in this project was mini-circuits ZOS-1025. This is a dual output VCO, one of the output is main output and another output is auxiliary output. In main output, this have output of typically +7 dBm while in auxiliary output it have -17 dBm across 685-1025 MHz range. The output signal had bandwidth of 2 MHz. Schematic of ZOS-1025 is shown in figure 17.



*Fig 17: Electrical schematic of ZOS-1025*

The frequency output of ZOS-1025 through main output was measured by spectrum analyser by tuning V-tune from 0 to 16 Volts. The result was as shown in figure 18.

Measurement condition: resolution bandwidth =1 kHz, video band-width= 1 kHz, V-tune= 0-16 V.



*Fig 18: Frequency response to input voltage on ZOS-1025*

Various loads were also connected to main output port and frequency drift on various load were measured through auxiliary output port. This experiment was done to see if VCO would drift its output frequency when load of different resistance is used and result was as shown in figure, various loading did not change frequency neither power level very much.

Measurement condition: V-tune=5V, Frequency=754.4 MHz, AUX\_OUT= -17.5 dBm and MAIN\_OUT=7.05 dBm, resolution bandwidth =1 kHz, video band-width= 1 kHz,

Table 2: VCO's output frequency and power level with different loads

Load (ohm)	AUX_Frequency reading (MHz)	AUX_Power reading (dBm)
47	754.4	-17.45
100	754.4	-17.53
150	754.4	-16.7
220	754.4	-16.7
330	754.4	-16.8

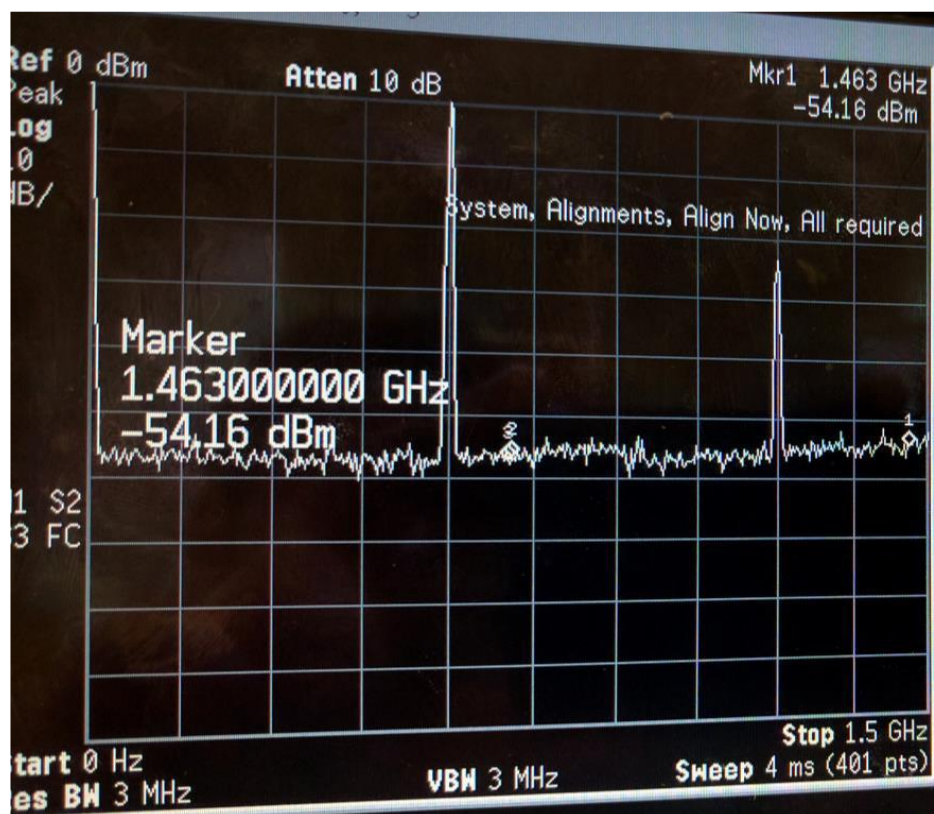
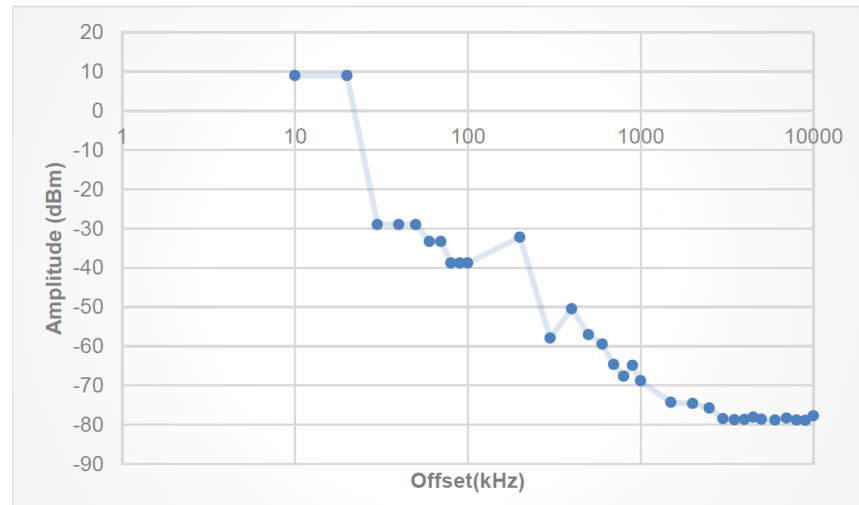


Fig 19: Output frequency components of VCO

It was found that VCO output signal had frequency components at primary frequency as well as whole number multiple of primary frequency as shown in figure 19. Primary frequency component was at 684MHz of 1.64 dBm and second component was at 1.37 GHz of -28.2dBm.

Phase noise of VCO was also measured. In this measurement 685 MHz was taken as centre frequency and amplitude of VCO's output was measured in various offset (offset in frequencies) from centre frequency. Result of this measurement is shown in figure 20.

Measurement condition: V-tune=2.4V, centre frequency=685 MHz, resolution band-width =1 kHz, video band-width= 1 kHz, amplitude at 685 MHz was 9 dBm.



*Fig 20: Power measured by spectrum analyser in various offset from peak frequency*

After these tests, it was concluded that ZOS-1025 was pretty stable and quit reliable for this project.

### 3.2 Mixer Testing

After selecting VCO, mixer was tested by feeding RF signal from VCO's output and IF from a signal generator.

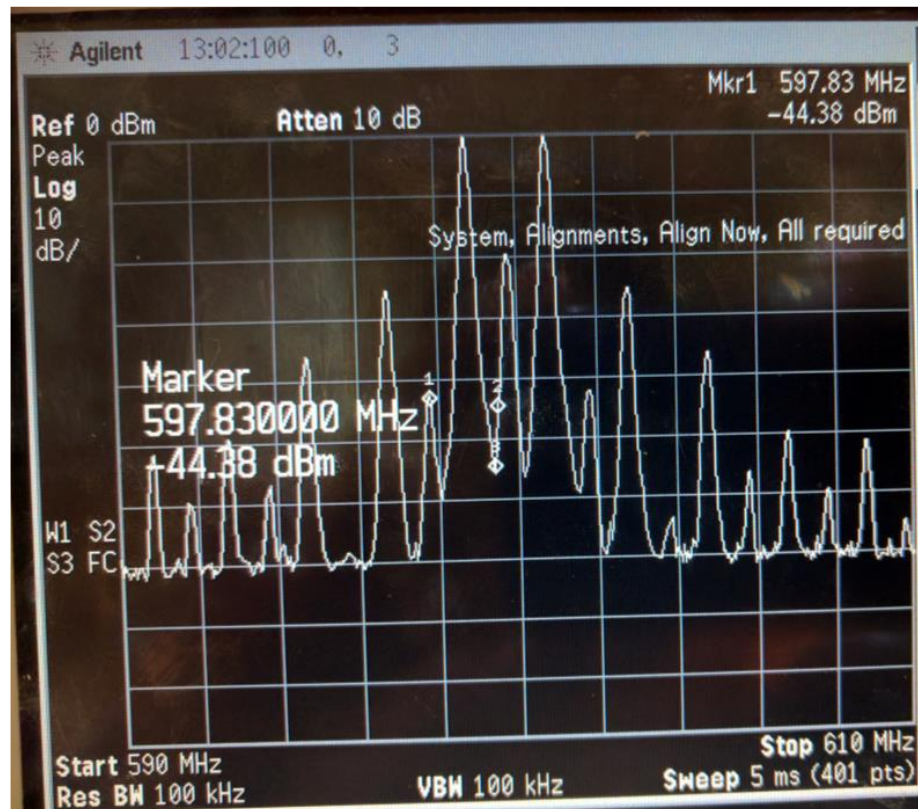


Fig 21: Mixer output frequency response

When mixer was tested it was found that mixer output had various other frequency components other than  $(f_1+f_2)$  and  $(f_1-f_2)$  as shown in figure 21. These frequency components were  $f_1$ ,  $f_2$ ,  $f_1+f_2$ ,  $f_1-f_2$ ,  $2f_1+f_2$ ,  $f_1+2f_2$ , etc. It was seen because mixer not only produces sum and difference in frequency of two input signals but also produces sum and difference in frequency of whole number multiple of these two input signals frequency.

Peaks seen in above figure 21 were measured and results are in table 3.

Measurement condition:  $f_1=685$  MHz 1.2dBm by VCO and  $f_2=50$  MHz 0dBm by signal generator, noise floor of spectrum analyser= -55dBm.

Table 3: Various frequencies components and power level seen in mixer output

Peak Position	Power (dBm)	Frequency (MHz)
Centre	-22.3	685
1 <sup>st</sup> left	-3.01	635
1 <sup>st</sup> right	-3.16	735
2 <sup>nd</sup> left	-46.0	586



2 <sup>nd</sup> right	-44.8	785
3 <sup>rd</sup> left	-30.7	537
3 <sup>rd</sup> right	-31.0	837
4 <sup>th</sup> left	-39.6	436
4 <sup>th</sup> right	-38.6	935

Then the mixer was tested by inputting various IF and RF frequency signals the result was found as table 4.

Measurement condition: resolution bandwidth =1 kHz, video band-width= 1 kHz, noise floor of spectrum analyser= -55dBm.

Table 4: Mixer results as up-converting mixer.

IF (MHz)	USB-RF (MHz)	LSB-RF (MHz)	USB (dBm)	LSB (dBm)	Centre frequency (dBm)
1	686	684	-1.29	-1.30	-21.51
10	695	675	-2.33	-2.17	-22.25
20	705	665	-2.49	-1.96	-22.32
30	715	655	-2.35	-1.79	-22.31
40	725	645	-2.81	-2.30	-22.46
50	735	635	-2.75	-2.44	-22.33
60	745	625	-2.83	-2.32	-22.47
70	755	615	-2.99	-2.27	-22.46
80	765	605	-3.24	-2.46	-22.37
90	775	595	-4.65	-4.00	-23.41
100	785	585	-4.77	-3.89	-23.36
200	885	485	-5.33	-3.80	-23.43
300	985	385	-3.79	-5.04	-23.25
400	1085	285	-5.29	-3.61	-23.11
500	1185	185	-6.02	-4.89	-23.64

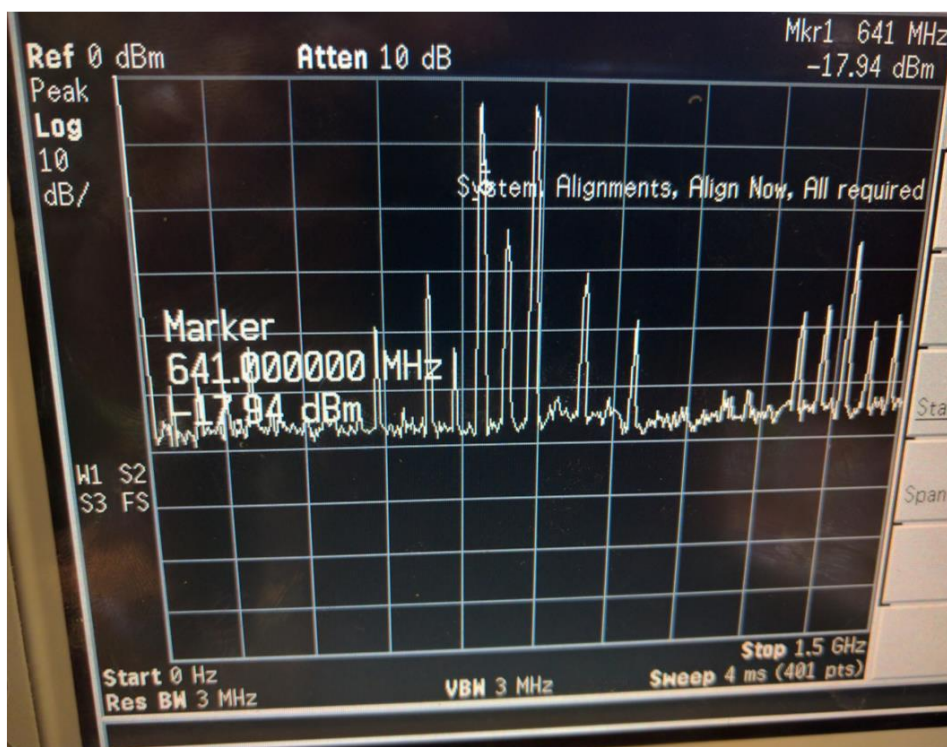


Fig 22: Mixer result due to presence of whole number harmonics in output of VCO.

It was found that mixing of LO and IF was happening in 685 MHz and 1.3 GHz frequencies as shown in figure 22. It happened because VCO had output with frequency component in its primary frequency as well as in whole number multiple of the primary frequency (figure 19). These VCO primary and its harmonics frequencies had also got to mixer input and affect output frequency response of mixer.

After these result, it was found that mixer was suitable for this project.

### 3.3 Filter Testing

This project needs two types of filter. One at 735 MHz, a bandpass filter and another at 50 MHz a low pass filter. Bandpass filter was fabricated. Whereas low pass filter was mini-circuits SPL50+.

Then S11 and S12 parameter of bandpass filter and S12 parameter of low pass filter was tested.

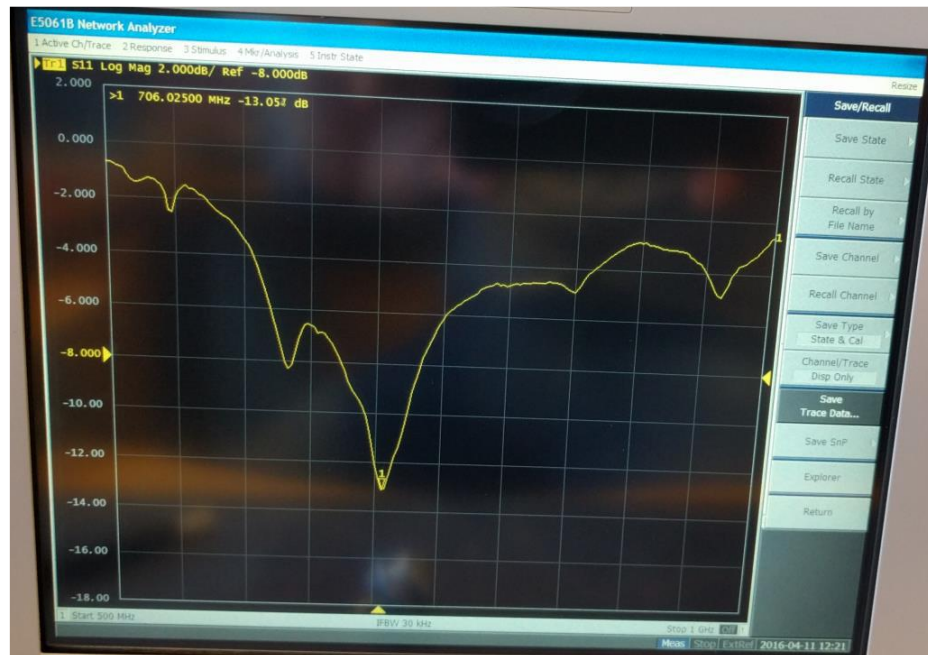


Fig 23: S11 parameter of bandpass filter

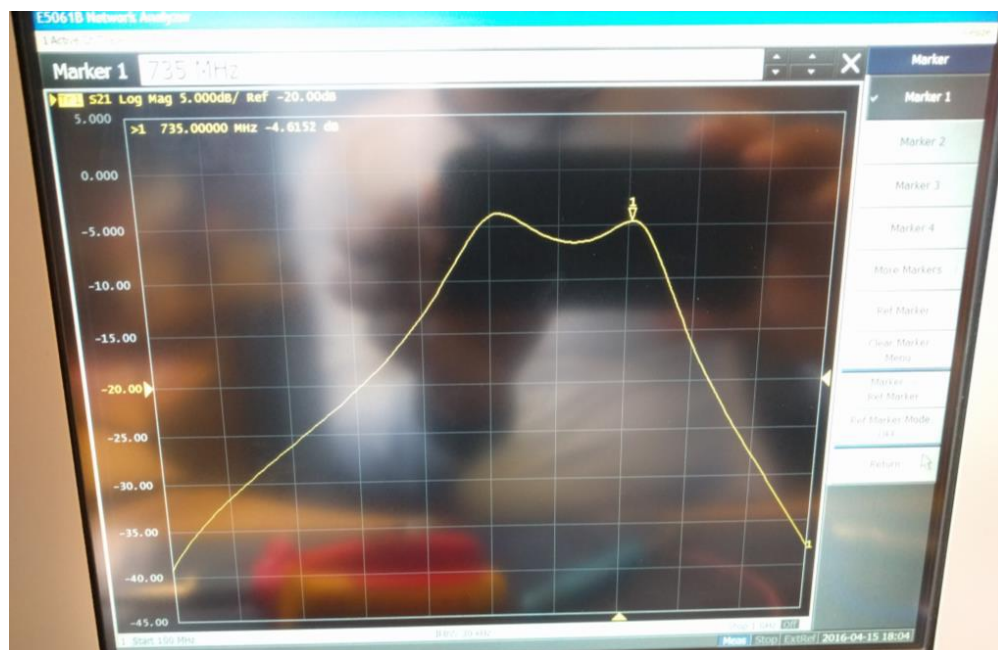
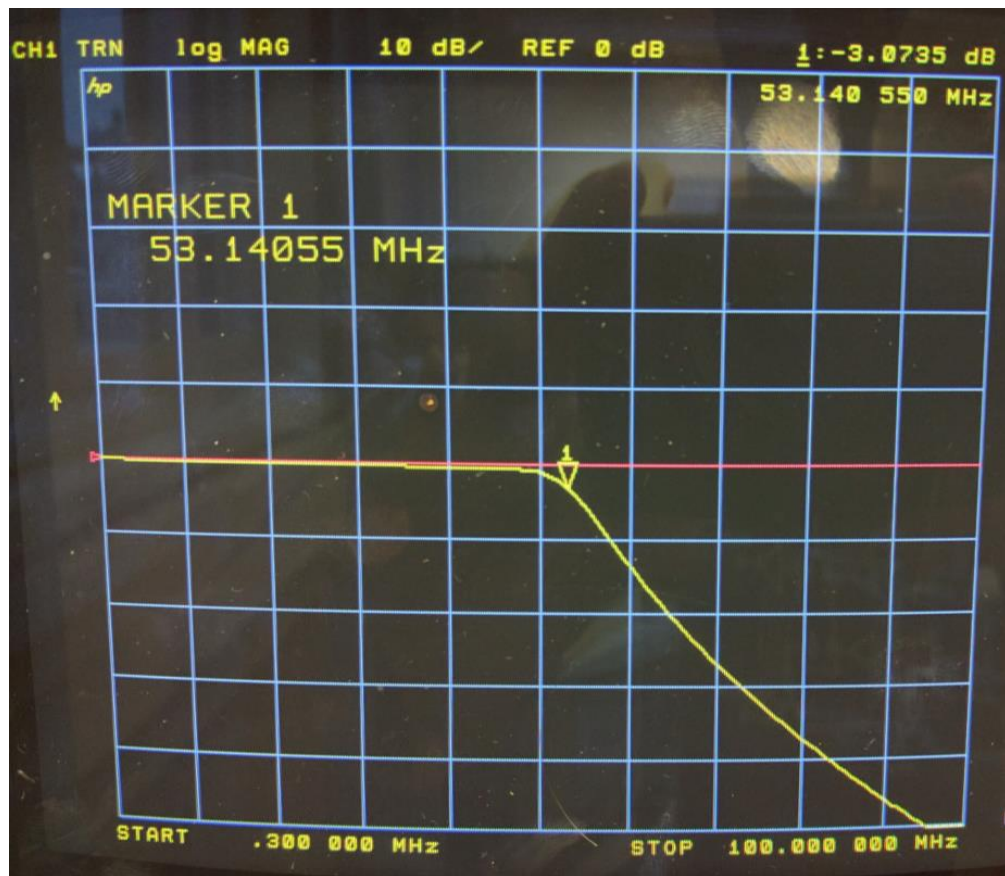


Fig 24: S21 parameter of bandpass filter

From figure 23 and 24 it is seen that filter was working as bandpass filter at 735 MHz. In figure 23, S11 parameter was measured. Here most reflection was at 706 MHz of -13 dBm. In 735 MHz, filter's had reflection of -11 dBm. In figure 24, filter was transmitting from 600 to 740 MHz frequency and blocking all others frequency components. From 600 to 740 MHz S21 parameter was in average of -5 dBm while in below 600

MHz, S12 parameter was decaying by 15 dB per decade while above 740 MHz S12 parameter was decaying by 20 dB per decade.



*Fig 25: Low pass filter frequency response.*

From figure 25, it can be seen that low pass filter had good frequency response. It had -3 dB point at 53.14 MHz and attenuation beyond 50 MHz was above 10 dB per decade.

After these tests, it was found that low pass filter had frequency response as required for this project. On the other hand, bandpass filter was a bit lousy. It was behaving like bandpass filter, but more tuning was required. In the other hand, antenna designed in this project had frequency response of bandpass filter as required in this project. Therefore instead of tuning bandpass filter more precisely, filter was removed and antenna was used as filter as well as antenna.



### 3.4 Antenna Testing

After fabrication of antenna, S11 and S12 parameters were tested using network analyser.

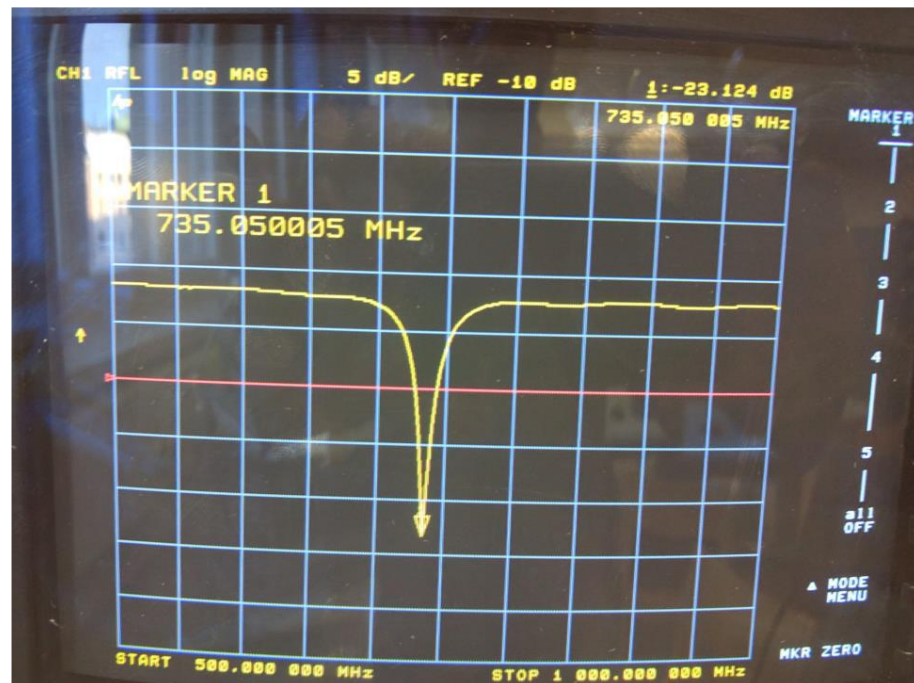


Fig 26: S11 parameter of antenna

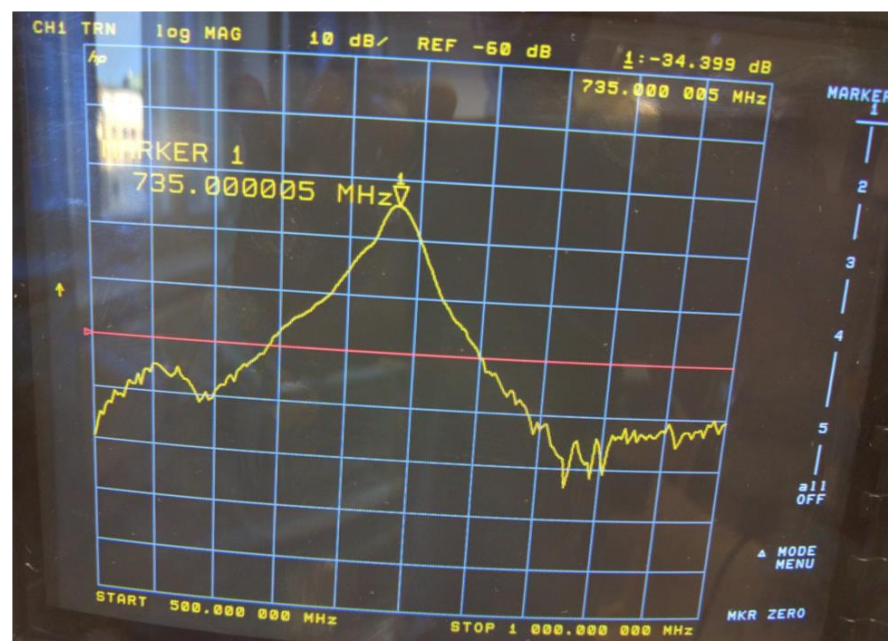
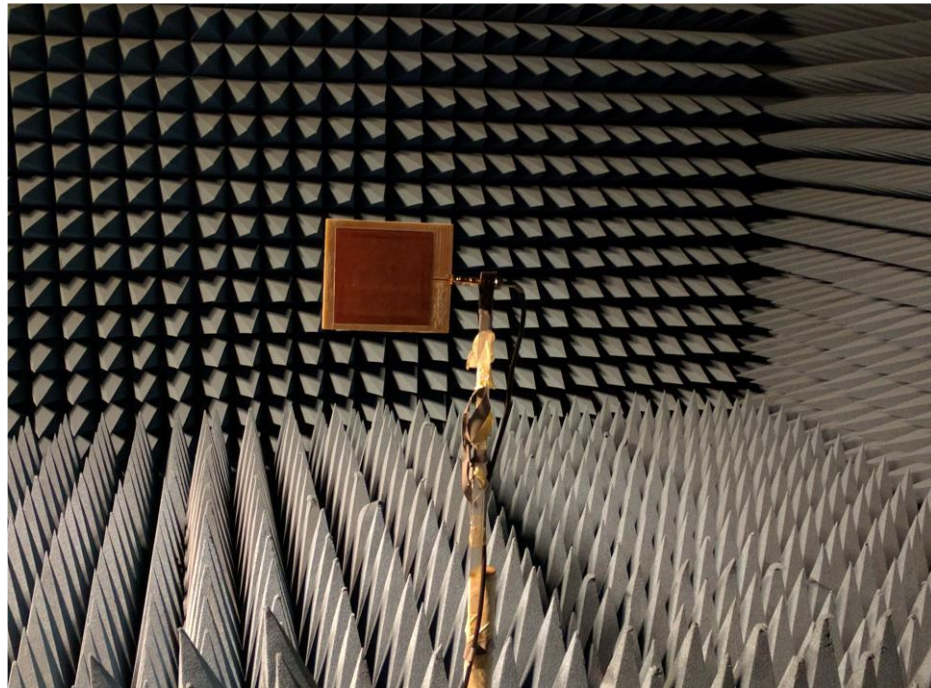


Fig 27: S12 parameter of antenna

From figure 26 we can see that the antenna had lowest S11 parameter at 735 MHz that mean at 735 MHz antenna had minimum reflections and everywhere else had high reflection. Minimum reflection would make maximum radiation. This is seen in figure 27 as well where at 735 MHz it had highest transmission and everywhere else transmission was low. Because of these two measurement (figure 26 and 27), it was concluded that patch antenna was well-tuned to transmit and receive signal at 735 MHz.

Then the antenna's radiation pattern was tested in anechoic chamber located in 6<sup>th</sup> floor of Metropolia University of Applied Sciences, Albertinkatu 40-42 facility. Picture of antenna in anechoic chamber is shown in figure 28.

Measurement condition: Network analyser start frequency= 500 MHz, stop frequency= 1GHz, scale = 10dB per division, reference = -80dB, rotation angle step = 5 degrees.



*Fig 28: Antenna setup in anechoic chamber*

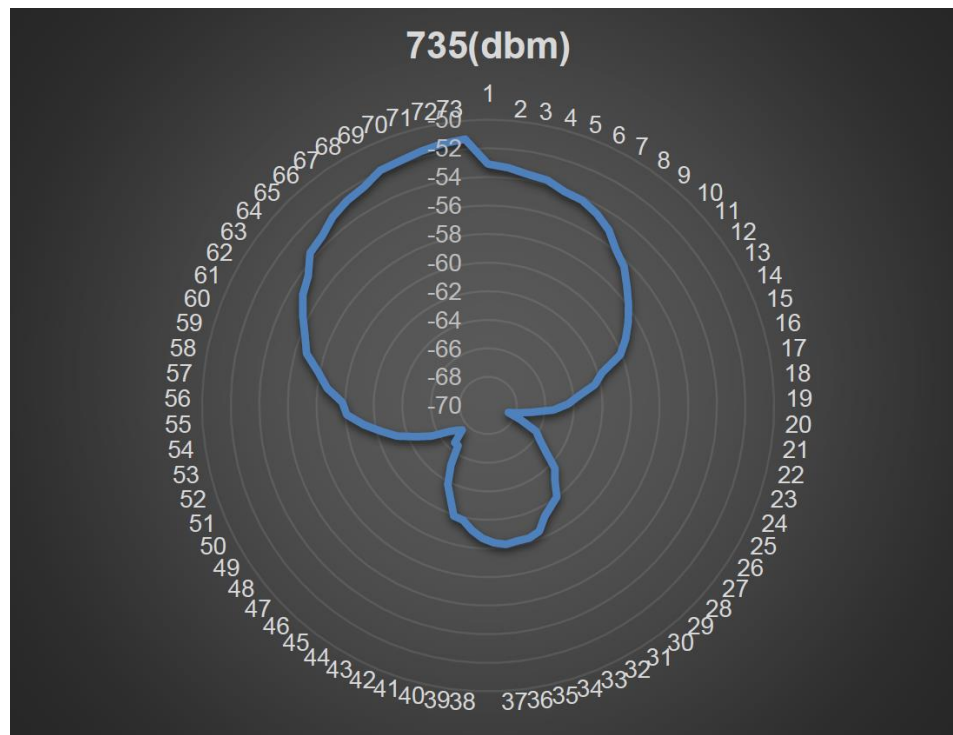


Fig 29: Vertical polarization of antenna

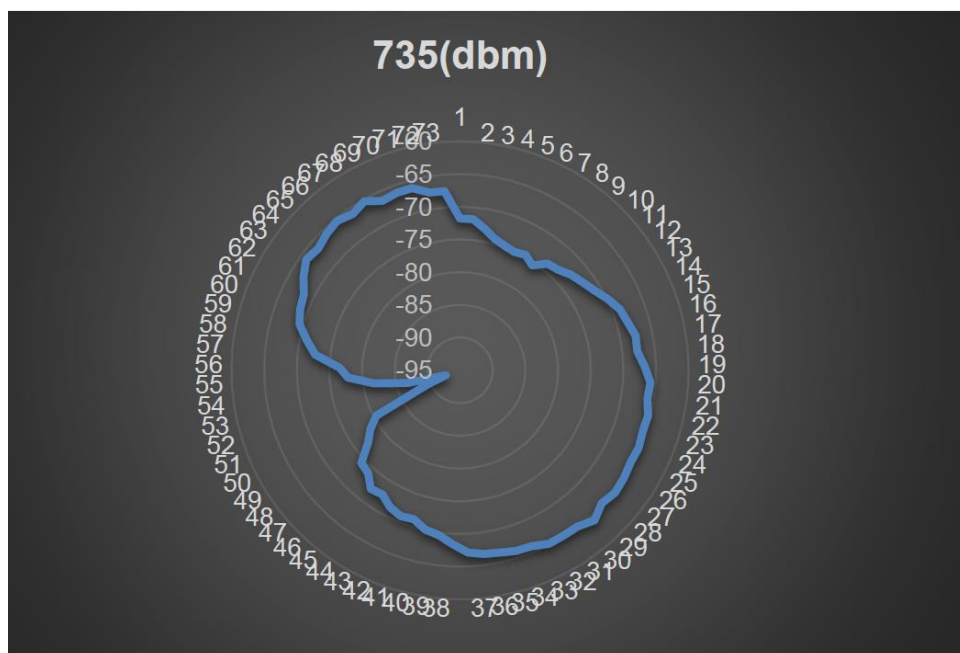


Fig 30: Horizontal polarization of antenna



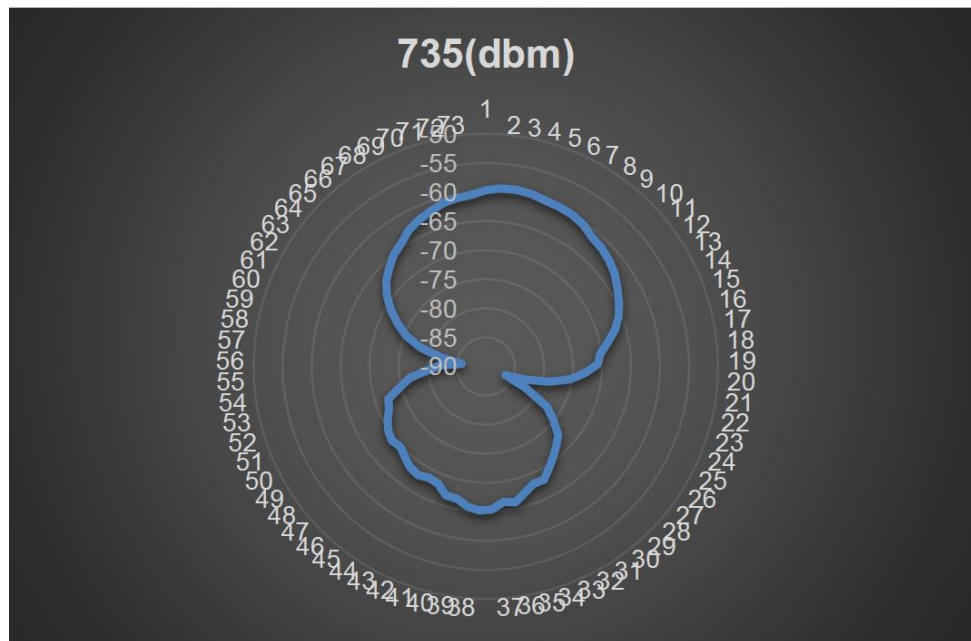


Fig 31: Cross polarization of antenna

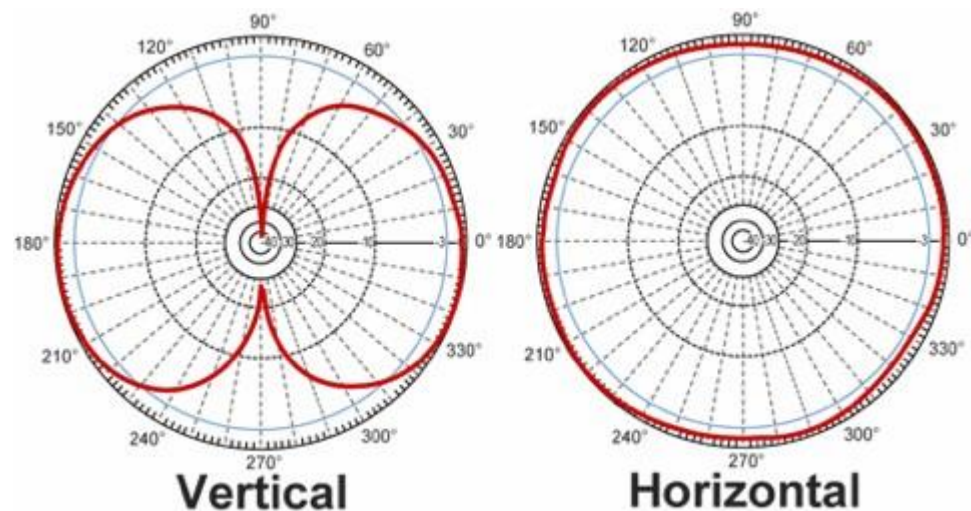


Fig 32: Ideal dipole antenna

Radiation pattern of an ideal dipole is given by figure 32. Where it has '8' shape radiation pattern in vertical orientation because it has good radiation in 0 degree and 180 degree and has poor radiation in 90 degree and 270 degree. In horizontal orientation it has 'O' shape because it is radiating isotopically.

In vertical orientation figure 29, it was seen that patch antenna had good radiation at 0 degree and had poor radiation at 90 and 270 degree. 180 degree had some radiation but it was not good as 0 degree. This means patch antenna radiates better to the side it



had patch structure compared to ground side. This can be seen once again in horizontal orientation as well in figure 30. Ideally it should have radiation pattern of 'O' shape. But it had maximum radiation when patch is facing toward transmitting antenna compared to opposite ground side. Cross polarization in figure 31 also had similar radiation pattern like vertical polarization. This was because patch structure of antenna was a square.

After measurements, it was found that antenna designed in this project was good enough for this project.

### 3.5 Radio Testing

In transmitting radio, power output of VCO was 1.2 dBm at 685 MHz. For information signal 50 MHz 0dBm signal was taken from signal generator. VCO's output and signal generator output went to mixer. The mixer produced output of 635MHz and 735MHz at -4dBm.

Antenna had very good bandpass filter like response (figure 26 and 27). 635 MHz was 30 dB smaller than 735 MHz. frequency response of antenna at 685 MHz is 15 dB smaller than 735 MHz. Signal power level at 685 MHz was 18 dB smaller than signal power level at 735 MHz, therefore signal at 685 MHz should be 30 dB smaller than 735 MHz. Thus only 735 MHz signal was being transmitted.

Two antennas were kept at 20 cm apart in vertical orientation. Power received by receiving antenna was -32.5 dBm at 735 MHz, -66.2 dBm at 686 MHz, -63.3 dBm at 635 MHz and -69.5 dBm at 783.5 MHz.

After down-converting mixer, signal power level was -39 dBm at 50 MHz, -72 dBm at 100 MHz and -72 dBm at 150 MHz.

After 50 MHz low pass filter, only 50 MHz frequency was seen at spectrum analyser at -40.5 dBm.

## 4 Conclusion

Goal of this project was to send a signal wirelessly through a radio, learn and understand how a radio functions.

First when this project was started, it was concluded that manufacturing all the components would not be possible. Therefore all available components in Metropolia's inventory were searched and then depending upon available components and their working frequency range, a transmitting frequency was selected. Those components which were not found were like filters and antennas were manufactured.

Then all those components were tested. Their various performance parameters were measured and examined whether those components would be appropriate for this project or not. After testing all the necessary components, a basic transmitter-receiver chain was built.

In the end of this project, the transmitter-receiver system designed was successfully able to transmit wirelessly and then recover back the 50 MHz bandwidth signal. This project have achieved its goal and this

In this project, filter was not very well tuned. If this project would be continued, a better well-tuned filter should be designed. Also information signal here was pure sinus of 50 MHz signal was used. It would be interesting to see what would be reception signal quality if some real information is sent through this design. Would we able to decode signal and understand information sent through this radio or not?

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